

IC/94/155

VALENCIA 93: THE SUMMARY OF PARTICLE THEORY

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February 7, 2008

Abstract

The International School on Cosmological Dark Matter held in Valencia in the fall of 1993 was devoted to the interplay of cosmology and particle physics, with the obvious emphasis on the Dark Matter issue. Here I present the expanded version of my summary talk regarding the particle physics theory part of the School.

1 Introduction

I am deeply aware that it is impossible to give a complete summary of a week long meeting, but I will still try, if for no other reason but for the months long push by the organizers. My task has been made easier by the fact that the summary of the cosmology part of the School has been done by Gary Steigman, although I still expect to fail.

My plan is the following. I will not discuss talks one by one, but rather go over what in my opinion were the highlights of the meeting, and what the important open problems of present day particle physics are. Needless to say my presentation will be subjective, if not biased, and I apologize to those speakers who may find their contributions ignored or not well presented. It will not happen for reasons of ignorance and bias only, but at least partially for the lack of time and space.

The theory part of the school started with my lectures on the standard model of particle physics. My enthusiasm in accepting this was highly motivated by Jose Valle's twisting my arm, although I should mention that he was nice enough to let me go, in his own words, *un poquito* beyond. I will concentrate here mostly on the *poquito* part, but for the sake of completeness we shall start with the Standard Model and its relation with cosmology. The second part of my review will then be devoted to the interesting extensions of the Standard Model, always keeping in mind cosmology.

2 The Standard Model and Cosmology

For the sake of clarity and in order to establish the notation and the conventions, let me define the Standard Model (SM) as the $SU(2)_L \otimes U(1)$ gauge theory of electroweak interactions with three families and one Higgs doublet.

We all know that the Standard Model is in excellent agreement with the experiment, far better than any of us would have imagined twenty years ago. There is not even a shred of evidence of any new phenomena beyond the electroweak scale M_W . It is then natural that we should turn to astrophysics and cosmology in the attempt to uncover some new physics. There are many such issues, but I will concentrate

on the few main ones only. As the name of the School dictates, we will start with the problem of the Dark Matter (DM), and go to the solar neutrino puzzle (SNP), baryogenesis, and then only briefly mention the problem of atmospheric neutrinos (AN).

Although phenomenologically extremely successful, the Standard Model suffers from two serious theoretical problems that encourage the search for a more complete theory.

1. **The problem of Higgs mass.** The scalar mass terms are not protected by any symmetry and so it seems that there is no mechanism that can prevent the Higgs particle from acquiring arbitrarily large mass. In other words, how do we keep $M_W \ll M_{Pl}$?
2. **The strong CP problem.** In the Standard Model the effective strong CP parameter

$$\bar{\theta} = arg(F\tilde{F} term)_{QCD} + arg(det M_q) \quad (1)$$

(M_q being the quark mass matrix) is not controlled in perturbation theory. It gets infinitely renormalized in higher orders in perturbation theory and thus the experimental constraint $\bar{\theta} \leq 10^{-9}$ remains a mystery (although it should be mentioned that the first finite contribution to $\bar{\theta}$ appears separately from the infinite part and is small) [1].

2.1 Dark Matter and The Standard Model

Here unfortunately there is basically nothing to be said. By definition neutrino is massless in the Standard Model (see below, though) and there are no other light enough particles to give us candidates for the Dark Matter. Thus, if we could be sure that there is non baryonic DM in the universe, this would be a clear signal for the new physics.

2.2 Solar Neutrino Puzzle

The solar neutrino puzzle (SNP) has been discussed extensively by Aleksei Smirnov. He did not discuss the magnetic moment solution to SNP, and so I will skip it too. We are left then with either

1. **MSW mechanism.** This, by far the most popular and elegant solution to SNP is based on the resonant neutrino oscillations in matter. It favors the neutrino mass difference and the mixing angle

$$\begin{aligned}
MSW : \quad \Delta m^2 &\simeq 10^{-7} - 10^{-5} \text{ eV}^2 \\
\sin^2 2\theta &\simeq 10^{-3} - 10^{-2} \text{ (small mixing)} \\
\sin^2 2\theta &\simeq 0.6 - 0.85 \text{ (large mixing)}
\end{aligned}$$

or

2. **Just-so solution.** This is the long oscillation length solution to SNP which corresponds to ν_e turning into ν_μ or ν_τ as it arrives to Earth from the Sun. In this case the same parameters become

$$\begin{aligned}
Just - So : \quad \Delta m^2 &\simeq 10^{-11} - 10^{-10} \text{ eV}^2 \\
\sin^2 2\theta &\geq 0.8
\end{aligned}$$

In what follows let me make the usual assumption that there is a solar neutrino puzzle and that it is a problem of neutrino physics. As I said neutrinos are massless and also they carry no magnetic moment according to the standard picture, hence the Standard Model can offer no light on SNP. Right? Wrong. Well, maybe wrong. Namely, the question is whether we should include gravity as a part of the Standard Model; it certainly would not be unreasonable to do so. Now, we say that neutrinos are massless in the Standard Model, since the lepton number is conserved and since by definition there are no right handed neutrinos. In other words, an effective interaction term

$$\nu_L^T C \nu_L \frac{(\phi^0)^2}{M} \quad (2)$$

(ϕ^0 is the neutral component of the Higgs doublet) can arise in higher orders only if B-L symmetry is broken (M would be the scale of B-L breaking). The essential point here is that gravity through its non-perturbative Planck scale effects (virtual black holes, virtual worm-holes, virtual... holes) may break B-L, which, as we know, is an accidental anomaly-free global symmetry in the Standard Model. Thus (2) could be generated with $M = M_{Pl}$, giving us

$$m_\nu = \frac{\langle \phi \rangle^2}{M_{Pl}}. \quad (3)$$

In other words, neutrino becomes massive with m_ν approximately $10^{-6} - 10^{-5} \text{ eV}$. And if $\Delta m_\nu^2 \simeq m_\nu^2 \simeq 10^{-12} - 10^{-10} \text{ eV}^2$, and if the neutrino mixing angles are large (a democratic acting of gravity?), this would suffice to provide the large oscillation length solution to the SNP [2]. This was discussed in my lectures.

2.3 Baryogenesis

Again the Standard Model offers an unexpected richness in providing all the ingredients needed for the creation of baryon asymmetry. The crucial point is the anomaly induced quantum mechanical breaking of the baryon number, otherwise classically conserved. The predicted baryon asymmetry n_B/n_γ is still subjected to an intense debate. It depends strongly on the nature of the phase transition at temperatures of order M_W , and it may be some time before we have a definite answer to this important, if not central, issue of the Standard Model. Furthermore, it is not clear if there is enough CP violation built in the Kobayashi-Maskawa mechanism to provide a large enough n_B/n_γ . I shall not go into details here for this was not discussed at the School (for a review, see [3]).

Let me stress though an important property of n_B/n_γ that could come out of the Standard Model. Since the CP-violation at $T = 0$ and at $T \leq M_W$ originate from the same source, you can in principle predict the sign of baryon asymmetry. By contrast, conventional GUTs fail in this respect since the new interactions of superheavy Higgs and gauge bosons contain new CP-phases, and there is no one-to-one correspondence between the signs of CP-violation at high and zero temperature. For example, the superheavy X bosons of $SU(5)$ with charges $-4/3$ have the following interactions [4]

$$L_{int}(X) = gX^\mu [\bar{P}_L^c \gamma_\mu K P_L] \quad (4)$$

where

$$P = \begin{pmatrix} u \\ c \\ t \end{pmatrix} ; K = \begin{pmatrix} e^{i\phi_u} & & \\ & e^{i\phi_c} & \\ & & e^{i\phi_t} \end{pmatrix} \quad (5)$$

in the basis where quark masses are positive numbers. The matrix K is completely independent of the Kobayashi-Maskawa matrix, thus

new phases. The same is true of other gauge boson and superheavy Higgs interactions.

It is clear that even in the Standard Model there may be rich implications for cosmology. However, as we have seen, the Dark Matter chapter is rather dull, and since the School was mainly devoted to Dark Matter, it is not surprising that we will go beyond *un poquito*.

3 Beyond the Standard Model

3.1 Supersymmetry

In recent years, Supersymmetry has grown to be the standard extension of the Standard Model. The reason is not just the structural beauty of the theory, but rather its role in providing a mechanism to keep the weak scale so many orders of magnitude below the Planck and GUT scales. A renormalizable theory such as the Standard Model should not know of large scales, but unfortunately the Higgs mass is sensitive to any new scale above M_W . For this reason, the Standard Model is crying for supersymmetry.

We can say that supersymmetry for Higgs mass plays the same role as chiral symmetry does for the fermion mass. A chiral symmetry makes $m_f = 0$ natural, and if we have supersymmetry clearly the vanishing of the scalar mass becomes natural too. For this to work in the real world, the scale of supersymmetry breaking should be of order M_W . This was emphasized in Graham Ross's lectures at the School. He has discussed extensively the phenomenology and cosmology of supersymmetry, and I refer you to his lecture notes. It is hard to overstress the richness of the supersymmetric phenomenology. We are to find the whole replica of our world with every fermion interchanged by a boson and viceversa at the energy range $1 - 10 TeV$.

In the minimal supersymmetric Standard Model, the superpotential assuming matter parity is

$$W = \mu H \bar{H} + g_u H Q U^c + g_d \bar{H} Q D^c + g_e \bar{H} L E^c \quad (6)$$

where H and \bar{H} are the necessary two Higgs doublet superfields with opposite hypercharges, and Q, U^c, D^c, L, E^c are quark and lepton

superfields respectively; $g_{u,d,e}$ are “Yukawa” coupling constants (family indices are suppressed) and μ is a mass parameter which has to be of order m_W for the correct electroweak symmetry breaking. It has a continuous global R-symmetry under which the respective charges are $R_H = R_{\bar{H}} = 1$, and $1/2$ for the rest of the superfields. Assuming soft-breaking terms coming from the hidden sector breaking of supergravity leads to the following expression for the potential

$$V = \sum_i \left| \frac{\partial W}{\partial \phi_i} \right|^2 + m_g A W^{(3)} + m_g B W^{(2)} + h.c. + \sum_i m_g^2 |\phi_i|^2 + (D - terms) \quad (7)$$

where ϕ_i are the scalar components of the superfields and $W^{(2)}$ and $W^{(3)}$ are its bilinear and trilinear (in ϕ_i) pieces respectively, A and B are numbers related to the details of the hidden sector, and m_g is the gravitino mass. The A and B pieces clearly break R-symmetry.

Notice that you still end up with a discrete R-parity symmetry under which H and \bar{H} are invariant and all others superfields (and the superfield variable θ) change the sign. This is equivalent to all usual particles being invariant and all supersymmetric partners being odd under R-parity. Thus the lightest supersymmetric particle (LSP), normally expected to be one of the neutralinos, is stable. This is true in any model where R-parity is not broken, i.e. in the models where the sleptons do not get a non zero vev

The important role of Supersymmetry in providing the Dark Matter of the Universe was discussed by Antonio Masiero. From what we said, the LSP becomes naturally a Dark Matter candidate. For details see Masiero’s lectures.

I do wish to emphasize one important property of supersymmetric Grand Unification. We said that Supersymmetry is tailor-made for the Standard Model Higgs mass problem; what comes as a bonus is that it also provides a way out of the proton lifetime problem of minimal Grand Unification. Namely, in minimal $SU(5)$ the proton is too short-lived and furthermore $\sin^2 \theta_W$ comes out to be too small. On the other hand the presence of the supersymmetric partners, if their masses are of order M_W , increases proton lifetime and in the minimal theory predicts correctly $\sin^2 \theta_W = 0.23$.

Another interesting aspect of Supersymmetry are the restrictions on the Higgs potential. With the most general soft-breaking term, the potential takes the form

$$V = m_1^2 \Phi^\dagger \Phi + m_2^2 \bar{\Phi}^\dagger \bar{\Phi} + (m_3^2 \bar{\Phi} i \tau_2 \Phi + h.c.) + \frac{g^2 + g'^2}{8} (\Phi^\dagger \Phi - \bar{\Phi}^\dagger \bar{\Phi})^2 \quad (8)$$

where Φ and $\bar{\Phi}$ are the Higgs doublets from H and \bar{H} superfields. It is not hard to see that we have an important prediction of the lightest Higgs particle being less than the Z boson. Unfortunately, this is somewhat obscured by the radiative corrections, as has been discussed by Rosiek.

Finally, the question is what happens to baryogenesis at the weak scale in the context of Supersymmetry. At the first glance the situation is analogous to the Standard Model one, but there is more to it. We heard from Massimo Pietroni that the high temperature behavior of supersymmetric theories is rather interesting; he and his collaborators find that there may be more CP-phases generated at high temperature. This may have important implications for baryogenesis. However, again this prevents one from computing the sign of baryon asymmetry.

Before going on, I would like to remind you that we still lack *the* explanation of the splitting of the large and the small scales (the so-called doublet-triplet splitting problem). For some interesting ideas in this direction, see [5].

It is clear that in this short review I cannot do justice to such an important subject as Supersymmetry. I refer you to Ross's lectures and also to Ref. [6]

3.2 Neutrino Physics and Cosmology

It is well known that there are almost as many neutrinos in the universe as there are photons, approximately 150 per cubic centimeter per species. Whether or not this neutrino sea determines the fate of the Universe depends clearly on neutrino mass. The mechanisms to generate appreciable neutrino mass have been discussed by me and in greater detail by Jose Valle. The principal framework to understand the smallness of neutrino mass lies in the see-saw mechanism [7], which

as is well known, leads to a neutrino mass strongly suppressed compared to the Dirac mass terms, m_D

$$m_\nu \simeq m_D \frac{m_D}{M_R} \quad (9)$$

where M_R is the mass of the right-handed neutrino (assume $M_R \geq M_W$). The crucial question we need to answer in order to make predictions is what is the value of M_R . We have mentioned before that $M_R = M_{Pl}$ is quite plausible; unfortunately except for the potential solution of the SNP nothing interesting would emerge in this case.

Some possible natural scales for M_R :

- $M_R = M_X \simeq 10^{16} \text{ GeV}$ (GUT scale)

Then,

$$m(\nu_\tau) \simeq 10^{-3} \text{ eV} \quad (10)$$

and other neutrinos much lighter. Obviously, this is too small to give us enough Dark Matter, but fits ideally with the values needed for the MSW solution of the solar neutrino puzzle.

- $M_R = 10^{11} - 10^{12} \text{ GeV}$ (an intermediate scale in $SO(10)$)

Now ,

$$m(\nu_\tau) \simeq 1 - 10 \text{ eV}, \quad (11)$$

ideally fitting the Dark Matter constraint. The MSW mechanism would then go through the lighter neutrinos mass splitting.

- $M_R \simeq M_W$ (electroweak see-saw)

The interesting feature of the electroweak see-saw is that the electron neutrino could be the Dark Matter of the Universe, and at the same time could provide an observable neutrinoless double beta decay (but no SNP). You could also generate M_R through a vev of some singlet scalar S_R which leads to the existence of a Majoron G , a Goldstone boson of B-L symmetry breaking [8]. For $M_R \simeq M_W$ the Majoron can be an important Higgs decay product since Higgs can now decay into two Majorons. This was emphasized by Valle and also by Romao. The heavy neutrinos can decay into ν_e and the Majoron, in accord with all the cosmological constraints.

Another important mechanism of neutrino masses is their radiative generation, which was discussed by Valle. The simplest prototype

model which implements this mechanism is that due to Zee, which consists in adding another Higgs doublet and a singlet charged field h^+ to the Standard Model. The B-L symmetry is broken either explicitly or spontaneously as above. Such models have a richer phenomenology than the see-saw ones (new Higgs scalars) and also the resulting neutrino masses and mixing angles have interesting patterns with some general potentially identifiable characters [9].

The Majoron idea can be naturally implemented in supersymmetry; all one needs to do is to break the global R-symmetry spontaneously. Models of this kind offer a rather rich phenomenology and have been covered in great detail by Romao and Valle.

Their important characteristic is that they can provide both Dark Matter and the MSW solution to the SNP.

As can be clear even from our brief discussion, taking SNP or DM constraints seriously leaves us still with a lot of freedom in the neutrino mass matrix. Suppose now that you take seriously both, and furthermore let us also take seriously the problem of atmospheric neutrinos. AN has been summarized nicely by Evgueni Akhmedov and basically it says that we observe about a half of the predicted ratio of muon to electron neutrinos in the atmospheric neutrinos. The simplest explanation could be oscillations of ν_μ into ν_e or ν_τ or even some new sterile neutrino. The relevant mass difference and mixing angle should be

$$\begin{aligned} AN : \quad \Delta m^2 &\simeq 10^{-3} - 10^{-1} \text{ eV}^2 \\ \sin^2 2\theta &\simeq 0.4 - 0.6 \quad (\nu_\mu \rightarrow \nu_\tau) \\ \sin^2 2\theta &\simeq 0.3 - 0.8 \quad (\nu_\mu \rightarrow \nu_e) \end{aligned}$$

If you insist on the minimal neutrino spectrum of only three ν 's, you are forced to assume an almost degenerate mass matrix, with a typical eigenvalue of 1 eV . Namely this is required by the DM constraint and the mass differences must be small in order to explain SNP and AN. This was discussed by Daniele Tomasini.

I find it rather interesting that a realistic possibility can follow from the see-saw mechanism together with some family symmetry [10]. Namely, in the simplest versions of $SO(10)$ or left-right symmetric models, there is a direct mass term for a left-handed neutrino

$$m(\nu_L) \simeq \alpha \frac{\langle \phi \rangle^2}{M_R} \quad (12)$$

where α is some dimensionless constant [11]. Augmented with a horizontal symmetry, this would imply a diagonal, degenerate neutrino mass matrix. In this picture the mass splittings and non-vanishing mixing angles have their origin in the usual see-saw contribution m_D^2/M_R .

On the other hand, it could be that there are additional light neutrinos (which must be sterile in order not to upset Z decays), as has been advocated strongly by Juha Peltoniemi. In this case it is not surprising that one can satisfy all of the above constraints without the necessity of a degenerate mass matrix. In general, one does not expect sterile neutrinos to be light, but Enrico Nardi showed us an ingenious example based on E_6 GUT which predicts naturally light sterile neutrinos.

3.3 Strong CP Problem and Axions

We said before that the strong CP problem is one of the central unresolved issues in the Standard Model. There are basically two different ways of resolving it.

1. **Dynamical relaxation or Peccei-Quinn mechanism.** The most elegant and the most popular solution to the strong CP problem still remains the Peccei-Quinn mechanism. By adding another doublet to the standard model, we introduce a $U(1)_{PQ}$ symmetry whose spontaneous breaking gives an axion, the would-have-been Goldstone boson if not for the instanton effects which give it a small mass. The astrophysical constraints imply that the scale M_{PQ} of $U(1)_{PQ}$ must satisfy $M_{PQ} \geq 10^9 \text{ GeV}$, and if M_{PQ} is a couple of orders of magnitude larger the axion could be the Dark Matter of the Universe.

Since all the couplings of the axion to the matter and light are inversely proportional to the scale M_{PQ} , it is not surprising that the axion has not been found yet. Both the cosmological implications and the search for the axion were described in detail by Turner.

Although a beautiful mechanism, the axion picture suffers from the ad hoc way in which it is introduced. It would be much nicer if $U(1)_{PQ}$ were an automatic consequence of some more fundamental symmetry such as for example the family or the

GUT symmetry. There may be more to this than esthetics, since this could be a way out of potentially catastrophic gravitational effects [12].

2. **Symmetry principle: P or/and T.** In this approach, the strong CP parameter $\bar{\theta}$ becomes a finite and calculable quantity in perturbation theory [13]. For example parity or left-right symmetry would imply

$$M_q^\dagger = M_q \quad (13)$$

and the departure from the hermiticity can be shown to be finite. Although both P and T are arguably more natural symmetries than a global $U(1)_{PQ}$ broken by instantons, the resulting models lack the simplicity and the beauty of the PQ mechanism.

4 Summary and Outlook

As I have tried to convey in these few pages, the Standard Model of electroweak interactions is in excellent shape. Its only fault may be the lack of the excitement of new predictions. This is especially true as far as cosmology is concerned. We have no DM candidate whatsoever, we have only a little hope of explaining the SNP. As far as baryogenesis is concerned, we must wait more before we will have a clear picture.

What can we expect from the new physics beyond the Standard Model? Let us summarize here the most interesting potential cosmological consequences.

4.1 Dark Matter

- **Neutrino.** Clearly, since we know that they exist and fill up the universe, neutrinos are the most natural candidates for DM. Assuming that one of their masses lies in the electronvolt region, they would provide what is called a Hot Dark Matter, HDM (they are relativistic at the time of decoupling). Interestingly enough, any of ν_e, ν_μ or ν_τ could be Dark Matter, if not all three of them.

It is no problem to come up with models that give the desired value of neutrino mass, the trouble is the opposite: there are

too many such models. We desperately need more information from solar and atmospheric neutrinos before we can distinguish between the many theories of neutrino mass. We have seen that if all the puzzles remain to be true, the neutrino mass matrix would be known to a good precision.

- **Axion.** Unlike neutrinos, axions are hypothetical particles. It is true though that their existence is theoretically well founded and, what is even more important, if they do exist they are likely to be the Cold Dark Matter (CDM) whose existence seems to be required from the recent COBE findings. Namely, unlike neutrino mass which is a free parameter with only an upper bound, the axion mass (or in other words, M_{PQ}) has to lie close to the desired CDM value. However, if the axion is not to be found we will have to consider the other candidate solutions of the strong CP problem.
- **Neutralinos.** The lightest of them (LSP), if stable, is clearly a natural candidate for the Dark Matter.

The ideal Dark Matter scenario after the COBE findings appears to be some percentage of HDM and the rest mostly CDM. My prejudice is that these roles are played by neutrinos and the axion. Of course there could be baryonic Dark Matter in the Universe in the form of MACHOs which were discussed by de Rújula and Masso.

4.2 Solar Neutrino Puzzle

It may not be certain that there is a Solar Neutrino Puzzle or that it may be related to neutrino physics. However, the most popular theoretical prejudice is that neutrinos are massive and thus mix, which makes them naturally oscillate into each other. If so, we have a beautiful MSW mechanism which is still *the* most natural explanation of SNP.

Although less elegant, the idea of long oscillation length (just-so) solution of SNP may result naturally from non-perturbative gravitational effects. In this case *we may not have to modify the Standard Model at all.*

4.3 Baryogenesis

Here we have a rather exciting situation. It is still not clear that the Standard Model itself cannot produce enough baryon asymmetry, the same can be said of its minimal supersymmetric extension. I shall not go into the controversy surrounding this issue.

Of course if it is necessary to extend the Standard Model it is easy to produce enough baryon asymmetry. For example one may simply enlarge the Higgs sector to two doublets and introduce new sources of CP violation. Or one may resort to the good old GUTs and produce enough B–L asymmetry which cannot be erased by the breaking of B+L symmetry through the anomaly. The problem is then that you lose the connection between the $K - \bar{K}$ system, and the baryon-number violating part of the theory, i.e. one cannot predict the sign of the asymmetry itself.

I would also like to add that it would be really nice to come up with a theory that predicts both the value and the sign of baryon asymmetry and simultaneously the amount of strong CP breaking.

4.4 Outlook

In summary, what can we expect in the years to come ? I would say that it is extremely likely that there is another Higgs doublet, for as we have seen almost any extension of the Standard Model points to it. This tells you that I believe that there is an elementary Higgs scalar to start with. Also, I for one would not be surprised if we discover a new world of supersymmetric partners. I am convinced that neutrino has a mass although what its value is is far from clear. My prejudice, based on cosmology, is that at least one of the neutrinos has a mass in the eV region as to give us the Hot Dark Matter. And if the Cold Dark Matter is necessary as it appears, I believe that it will be in the form of axions.

So much about my prejudices. I hope the future will prove me completely wrong. Notice however that we may not have to change the gauge structure of the Standard Model at all. As we have seen, all the essential extensions of the Standard Model such as Supersymmetry, Peccei-Quinn symmetry and those that provide neutrino mass and enough baryon asymmetry may all be constructed within the $SU(2) \otimes U(1)$ gauge theory.

Acknowledgements

I have not only enjoyed this excellent meeting and the beautiful city of Valencia; it is here that I broke the ice and started to speak spanish. Quisiera expresar mi agradecimiento a los organizadores de la Escuela, especialmente a Fernando Pérez y Jose Valle por su hospitalidad y por haberme dado la oportunidad de ver los mejores fuegos artificiales del mundo.

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